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NACA

RESEARCH MEMORANDUM

EXPLORATORY TESTS OF TRANSPIRATION COOLING ON A POROUS 8° CONE AT M = 2.05 USING NITROGEN GAS, HELIUM GAS, AND WATER AS THE COOLANTS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
June 3, 1955

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SUMMARY

The effectiveness of transpiration cooling on an 8° total-angle conical body having a porous skin is presented for various coolant mass flow rates of nitrogen gas, helium gas, and distilled water. The tests were made under steady flow conditions in a free jet at a Mach number of 2.05, and at a Reynolds number of 8.0×10^6 based on approximately sea-level conditions and on the length of porous section investigated. Good agreement for the nitrogen tests was obtained with a theory for transpiration cooling. Helium gas gave the same reduction in heat transfer for less flow rate than the nitrogen gas. Tests with distilled water gave a large reduction in the average skin temperature. In the transpiration tests of this report, the model was completely cooled for a rate of 3.57 lb/min-ft^2; whereas for the film-cooling tests cooling the same model required 3.78 lb/min-ft^2.

A reference test without cooling was made to determine recovery factors which are in agreement with theoretical values.

INTRODUCTION

The aerodynamic heating of bodies at supersonic flight speeds has been investigated experimentally by many investigators, for example, in references 1 and 2. It can be seen from reference 2 that, for a transient trajectory where the Mach number varied from 0.55 to 5.18, the maximum measured skin temperature was 1,200° F. This temperature approaches the temperature limitations of structural materials commonly used in the manufacturing of missiles. Higher Mach numbers at higher Reynolds numbers for thin-skin missiles may be limited by the structural material used.

A possible method of reducing the heat transfer from the boundary layer to the missile surface is that of forcing a coolant through a porous wall, thereby diminishing the aerodynamic heat transfer to the surface. Accordingly, the Langley Pilotless Aircraft Research Division has conducted exploratory tests to determine the value of transpiration cooling as a means of reducing the aerodynamic heating.

Theoretical investigations of the effect of transpiration cooling have been reported in references 3 and 4, and some experimental tests have been reported in reference 5, in which the experimental data, although subsonic, agreed with the theory of reference 3. The present tests were conducted at a Mach number of 2.05 and approximately sea-level conditions. The experiments were made on an 8° total-angle porous cone where nitrogen gas, helium gas, and distilled water were each used for the coolant.

SYMBOLS

M	Mach number
V	velocity, ft/sec
h	aerodynamic heat-transfer coefficient, Btu/(sec)(sq ft)(°F)
ρ	density, slug/cu ft
μ	absolute viscosity of air, slugs/ft-sec
k	thermal conductivity, Btu/(sec)(sq ft)(°F/ft)
c_p	specific heat at constant pressure, Btu/(slug)(°F)
T	temperature, °R
C_H	Stanton number, $h/c_p\rho V$
R	Reynolds number, $\rho V l/\mu$
l	length, ft
C_f	skin-friction coefficient
Pr	Prandtl number, $c_p\mu/k$
W	coolant flow rate, slug/(sec)(sq ft)

L latent heat of vaporization, Btu/slug

A surface area, sq ft

Subscripts:

∞ local conditions outside boundary layer

aw adiabatic wall

s isentropic stagnation

w conditions pertaining to wall

c coolant

TEST APPARATUS AND MODEL

Preflight Jet

This investigation was made in the preflight-jet test apparatus located at the Langley Pilotless Aircraft Research Station, Wallops Island, Va. This test facility is described in reference 6. The air supply was sufficient to enable continuous testing for approximately 50 seconds at the desired test conditions. A shadowgraph system was provided for flow observation.

Model

The conical model used for these tests is shown in figure 1 installed in the test position in the 8-inch-diameter jet. Details of the construction of the model are shown in figure 2. The total apex angle of the model was 8°. The porous section through which the coolant passed was welded to a solid tip of stainless steel at the 3.6-inch station and to a brass ring at the 12.0-inch station. The porous section was formed by rolling sintered powdered stainless-steel sheet 0.0323 inch thick into the form of a frustrum of a cone and joining by means of a welded butt joint. The longitudinal welded butt joint produced a nonporous strip approximately 1/8 inch in width. The surface area of the porous section of the cone was 0.1865 square foot.

The complete specifications for the porous material are given in reference 7. Those specifications pertinent to these tests are given as follows: (1) The nominal flow capacity was to be 40 cubic feet of air per minute per square foot with a pressure drop of 2 pounds per square inch, (2) the openings were to be such as to restrict the passage of particles whose largest diameter exceeded 5 microns, (3) the apparent density was not to exceed 0.235 pound per cubic inch, and (4) the porous material was to be clean and free from foreign materials or external defects detrimental to fabrication or performance of parts.

The actual measured surface roughness was 80 microinches root mean square which was obtained by a profilometer having a probe of 0.0005-inch diameter.

Cooling System

The coolant was piped to the porous section and the mass rate of flow was measured by means of the system shown in figure 3. For the tests in which distilled water was used as a coolant, the water was forced from the storage tank by nitrogen gas applied through a pressure regulator. The water passed through a filter, a metering orifice, and then to the porous section by a pipe inside the model. The pressure drop across the porous surface was sufficient to insure that the cone was completely filled with water for all the heat-transfer tests reported. The mass rate of flow of the water was continuously measured during the test by recording the pressure drop across the calibrated metering orifice. The pressure drop across the metering orifice was made large compared to any conceivable fluctuation in coolant pressure downstream of the orifice to insure constant mass flow rate. The water temperature in the model was obtained by applying a calibrated correction to the temperature which was recorded by a thermocouple installed in the supply line. The supply of cooling water was permitted to attain approximately ambient temperature before use to insure minimum variation of water temperature during the tests.

For the tests in which nitrogen and helium were used, the water tank and filter were disconnected from the system and the coolant gas was piped directly to the cone from several tanks of nitrogen or helium, which were manifolded together to insure constant supply for each test. The mass rate of flow was measured by a thick flat-plate sharp-edge orifice as described in reference 8. The gas temperature was measured by a thermocouple installed in the supply line and was recorded continuously during each test. To obtain the gas temperature in the model, this supply-line gas temperature was corrected with a calibration factor obtained from other tests.

Temperature Measurements

In order to provide measurements of the skin temperature of the model, a total of 12 iron-constantan thermocouples made of No. 30 gage wire were attached to the porous skin. The thermocouples were arranged so that any thermocouple was at least 90° from the longitudinal seam. The location of the thermocouples is shown in figure 2. The thermocouple stations were spaced approximately $1\frac{1}{4}$ inch apart, the first being 4.56 inches and the last 10.81 inches from the apex. Three thermocouples were installed 90° apart at stations 5.81, 8.31, and 10.81. All thermocouples were installed by fusing the junction to the inner surface of the porous skin. Temperature gradients through the skin were assumed to be negligible. The effect of coolant on thermocouple readings was also assumed to be negligible because of the small cross-sectional area of the thermocouple wires in comparison with the porous-surface area. The thermocouple leads were taken out through the base of the model and down the rear of the model support strut as shown in figure 1. In order to prevent any leakage of the coolant through the rear of the model, the thermocouple leads were sealed into a metal sleeve. Pressure seals were provided on the outer surface of the sleeve to seal the coolant. A common cold junction was provided for all thermocouples. Continuous time histories of the thermocouple potentials were automatically recorded during the tests on multiple-channel recording galvanometers. All automatically recorded measurements were time synchronized by a 10-cycle-per-second electrical timing system.

TESTS

All tests were performed with the model mounted in the jet at zero angle of attack and yaw and with the nose tip approximately 3 inches inside the nozzle as shown in figure 1. The tests were made in a free jet at $M = 2.05$ and at approximately sea-level conditions.

The tests were performed by setting the mass rate of flow of the coolant and then starting the supersonic jet. Approximately 5 to 8 seconds were required for the jet to establish steady flow from the nozzle at $M = 2.05$. Steady flow was maintained until several seconds after the measurements of skin temperature indicated that the model had attained essentially equilibrium temperature. The variation of temperature of approximately 1° per second which occurred at the ends of the tests were negligible in comparison with the temperatures measured. Data are presented for four tests using nitrogen gas as the coolant, three tests using helium gas as the coolant, and four tests using distilled water as the coolant. All tests were made for various rates of coolant mass flow.

To provide a basis for evaluating the effectiveness of transpiration cooling, a test was performed without coolant. This test provided measurements of recovery factor.

RESULTS AND DISCUSSION

Reference Test Without Coolant

The boundary-layer recovery factor is defined as

$$\frac{T_{aw} - T_\infty}{T_s - T_\infty} \tag{1}$$

The effects of radiation and the effects of heat conduction along the skin on the heat transfer were calculated and found to be negligible compared to the heat transferred to the skin from the boundary layer. The air in the storage spheres and the supply of heat in the heat exchanger of the preflight-jet test apparatus limited the duration of tests under steady flow conditions to about 50 seconds so that equilibrium conditions could be approached closely but not exactly attained. The measured ratio of skin temperature to stagnation temperature for each thermocouple was plotted against the reciprocal of time and the nearly linear curve so obtained was extrapolated to infinite time. The recovery factors were computed for the values of temperature at infinite time so obtained. The recovery factors are shown in figure 4 plotted against the distance from the apex of the cone. For comparison is shown the theoretical recovery factor for a turbulent boundary layer which is equal to $Pr_w^{1/3}$, based on the wall temperature. The close agreement of the recovery factors with the theoretical value indicates that the boundary layer was turbulent.

Boundary-layer transition on the cone was assumed to occur 3.5 inches from the nose tip $(R = 4 \times 10^6)$ because, at this station, roughness due to the welding of the porous cone to the solid tip was approximately 0.01 inch high and the shadowgraph indicated a shock wave emanating from this region. Figure 5 is a shadowgraph taken during a nitrogen cooling test which shows the shock waves emanating from the 3.5-inch and 12-inch stations due to welds, from two intermediate stations due to shock reflections, and from the base of the faired support. The test Reynolds number based on the length from the 3.5-inch station to the last measurement station, and on conditions outside the boundary layer was approximately 8×10^6 for all the tests.

Tests With Coolants

The physical concept of transpiration cooling with gases is discussed in reference 9 and is briefly restated in the following paragraphs.

For transpiration cooling with gases, the cooling film on the outside surface is continuously renewed and there is a continuous movement of the gas away from the surface, because new coolant is continuously forced through the pores and then leaves the surface. A counterflow is thus created between the heat flowing from the hot boundary layer toward the surface and the gas flowing away from the surface. The gas continuously carries heat away from the surface by convection and in this way decreases the overall heat transfer to the surface.

For steady-state conditions, the rate at which heat is absorbed by the cooling gas through an element dA of the surface is, for conditions where radiation normal to the surface and conduction along the surface are negligible,

$$Wc_p(T_w - T_c)dA \tag{2}$$

where T_w is the final temperature of the coolant and equal to the wall temperature. The rate at which heat is conducted from the boundary layer through the coolant film to the surface is defined with a heat-transfer coefficient by the expression

$$h(T_{aw} - T_w)dA \tag{3}$$

In the above expression T_{aw} was obtained from the test without coolant. For the tests with nitrogen and helium, T_{aw} was corrected for the effect of transpiration rate on the recovery factor as shown in reference 4.

Equating the heat absorbed by the coolant (expression (2)) to the heat from the boundary layer (expression (3)) and solving for the aerodynamic heat-transfer coefficient gives

$$h = \frac{Wc_p(T_w - T_c)}{T_{aw} - T_w} \tag{4}$$

The above expression for the heat transfer is only true if radiation normal to the surface and conduction of heat along the surface are negligible. These effects were calculated and found to be of the order of 0.2 percent of the aerodynamic heat transferred; this value was considered to be negligible for these tests.

For the case where a coolant such as water has a change of state, a large reduction of heat transfer would be obtained by the heat of vaporization if boiling took place within the porous skin. Equation (4) would then be

$$h = W\frac{c_p(T_w - T_c) + FL}{T_{aw} - T_w} \tag{5}$$

where F is the fraction of water evaporated. However, since the amount of vaporization in these tests was not known, the reduction of heat-transfer data was accomplished by use of equation (4) which neglects the heat of vaporization. The heat-transfer coefficients so obtained thus represent a minimum and are valid only if vaporization did not exist.

In table I, the measured skin temperatures and other data pertinent to the tests are presented. It is seen that axial-temperature differences existed and that a considerable difference in the skin temperature also occurred around the circumference at some stations. These differences could have been caused by the nonuniform porosity of the porous material. After the investigation of transpiration cooling was concluded, the test with no coolant was made in which the model reached approximately equilibrium temperature and in which the thermocouples indicated about the same skin temperature to within 10° F. This agreement verified that the thermocouples were measuring the correct skin temperature during transpiration-cooled tests and that the difference in skin temperature for the transpiration-cooled tests was due to nonuniform porosity of the skin. Because of this variation of skin temperature, it was felt that presenting the average heat-transfer data for various coolant flow rates would show the overall effectiveness of transpiration cooling. In figure 6, the average heat-transfer data are presented for the tests in which nitrogen, helium, and distilled water were each used as the coolant. The average heat-transfer coefficients are presented as the ratio of Stanton number C_H to the theoretical $C_{H_{W=0}}$ for no coolant flow on a cone for a turbulent boundary layer. This ratio is plotted as a function of the coolant flow rate divided by the local (outside boundary layer) stream mass flow rate. The theoretical value of $C_{H_{W=0}}$ for no coolant flow on a cone was obtained from reference 10 and modified according to reference 11 which states that $C_{H_{W=0}} = 1.24C_f/2$. The local values of heat-transfer coefficients so obtained then were integrated over the length of the porous section of the cone and an average value of $C_{H_{W=0}}$ was calculated. The average heat-transfer coefficients as presented in figure 6 may have been more valid if empirical results could have been used as a basis for comparison with the theory in reference 3. However, it is felt that the theoretical basis which was used is sufficient in these exploratory tests to show any major deviations from the theory and is also adequate as a basis on which to compare the relative effectiveness of the three coolants used.

For the transpiration tests, the skin-temperature measurements shown in table I were faired by considering both the radial and the axial variations in temperature, and the local values of the heat-transfer coefficient were then calculated from equation (4). An average value of the heat-transfer coefficient was obtained by integrating the local values over the length of the porous cone, from which an average value of C_H was then calculated. In figure 6, the results obtained from this investigation are shown for various flow rates of nitrogen, helium, and distilled water. The data for the test with nitrogen at a $T_W/T_\infty \approx 1.5$ and $R_\infty \approx 8 \times 10^6$ based on the length from the start of porous section to the last measurement station are in good agreement with the theory from reference 3. This theory was developed for transpiration cooling with air, and comparison with the nitrogen tests only is valid because nitrogen and air have about the same thermodynamic properties. The data show a reduction in the heat-transfer coefficient of approximately 37 percent for a flow-rate ratio of 13.6×10^{-4} for nitrogen, whereas helium gave approximately the same reduction in heat-transfer coefficient for about one-third the flow rate. This difference in heat-transfer coefficient was expected since the specific heat of helium is about five times the specific heat of nitrogen. The thermodynamic properties for the coolants were obtained from reference 12.

As shown in the lower part of figure 6, a large reduction in heat transfer was obtained by using water for the coolant. The heat balance was made for the heat absorbed by the coolant in rising from the initial temperature to wall temperature, disregarding any heat absorbed from vaporization. For all these tests, it was observed that a water film existed on the outer surface of the model. The heat transfer is shown for various water flow rates that cooled the model to about 140° F for the lowest rate and 125° F for the highest rate.

In figure 7, the average skin temperature from the test results is shown in the term $\dfrac{T_W - T_c}{T_{aw} - T_c}$ and is plotted as a function of the mass-flow ratio. This figure provides a simple way of predicting the skin temperature for a transpiration-cooled cone at $M = 2.05$ and $R = 8.0 \times 10^6$ for the various coolants shown.

Figure 8 shows the temperature time history for a water-cooling test having a lower rate of coolant flow (0.0074 lb/sec) than those presented in figure 7. The figure shows that most of the thermocouples were cooler than the boiling point of water (212° F). However, thermocouples 7, 9, 11, and 12 at some time during the test indicated skin temperatures of 400° to 500° F. This rise of temperature on these four thermocouples can be accounted for by the orientation of the cone. The black dots on the cone as seen in figure 1 show the line of thermocouples 1, 3, 5, 7, 9, and 11 to be rotated clockwise approximately 30° from top center facing upstream. It can be seen that for this low rate of flow, the water did not completely fill the cone and that a water line could have existed just below thermocouples 7, 9, 11, and 12.

The area below the water line which existed in the cone for this test was estimated to be 0.13 square foot, which was approximately

70 percent of the total area of the porous section of the cone. The actual flow rate per unit area below the water line was unknown because some water was being evaporated from the water surface in the cone. Because of this uncertainty in the rate of flow, no heat transfer was presented for this test.

By comparing these results of transpiration cooling with water with that of the film-cooling tests of reference 6, it can be seen that, in order to completely cool the same model by transpiration cooling, a rate of 3.57 lb/min-ft^2 of coolant was required for $T_{aw} - T_w = 436^\circ$ F, whereas for film cooling, the method of reference 6, for $T_{aw} - T_w = 380^\circ$ F, a rate of 3.78 lb/min-ft^2 was necessary. A rate of 2.75 lb/min-ft^2 is quoted in reference 6 for a case where cooling was achieved for only 3 inches aft of the point of injection. It is felt that if the porosity of the material used in the transpiration-cooling tests reported herein was reduced so that the cone would be completely filled with water, a still lower rate of flow would give approximately the same cooling.

CONCLUDING REMARKS

The exploratory tests of transpiration cooling on a porous cone at a Mach number of about 2 and approximately sea-level conditions show the effectiveness of nitrogen, helium, and water used as coolants.

The average heat-transfer coefficients for the tests using nitrogen gas for the coolant were in good agreement with the predictions from theory. A reduction of 37 percent was obtained for a given nitrogen-gas flow rate; whereas, for cooling with helium gas, which has a much higher specific heat, the same reduction was obtained with about one-third the mass flow rate. Transpiration-cooling tests with water gave a large reduction in average wall temperature for a flow rate of 3.57 lb/min-ft^2.

In the transpiration tests the cone was completely cooled for a rate of 3.57 lb/min-ft^2, whereas complete cooling of the same nose for film cooling required 3.78 lb/min-ft^2.

It is felt that approximately the same reduction in heat transfer could be obtained for a lower water rate by decreasing the porosity of the porous wall to keep the cone filled with water.

Boundary-layer recovery factors measured for a test in which no coolant was used are in agreement with the theoretical value for a turbulent boundary layer.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 16, 1955.

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    Vol. VI, 1929.

TABLE I

TABULATION OF BASIC DATA

Coolant					Air jet		Skin temperatures at thermocouples, °F											
Type	Flow rate, $\frac{lb}{sec\text{-}ft^2}$	Temp., °F	[a] Δp	[b] p	[c] H_o	[d] T_o	1	2	3	4	5	6	7	8	9	10	11	12
							Station 3.66	Station 4.56			Station 7.06	Station 8.31			Station 9.56	Station 10.81		
Nitrogen	0.0410	135	313.6	44.1	111.9	563	365	380	428	398	430	474	483		424		439	458
Nitrogen	.0665	103	233.7	74.1	116.7	541	286	322	364	317	358	416	417	337	350	351	397	385
Nitrogen	.1287	86	216.0	112.8	116.2	548	241	261	310	265	313	380	377	213	283	288	311	335
Nitrogen	.2200	55	219.5	190.2	114.3	569	204	214	266	232	269	341	330		229	220	246	290
Helium	.0236	102	144.7	59.5	114.1	579	278	278	317	308	318	405	435		344	408	370	398
Helium	.0429	100	181.5	111.2	114.8	572	225	243	297	267	297	349	362	216	257	307	285	322
Helium	.0751	109	184.7	192.5	113.5	609	177	193	237	203	237	230	284	171	194	242	214	251
Water	.0595	92	99.8	17.1	114.0	638	145	133	126	139	131	143	200	154	136	136	139	136
Water	.0670	90	165.9	17.7	115.0	621	131	128	128	133	128	158	202	147	138	135	135	135
Water	.0825	93	83.9	19.4	114.5	640	125	122	125	125	123	138	184	133	113	125	125	128

[a] Δp is pressure drop across measuring orifice measured in pounds per square inch.

[b] p is pressure downstream of measuring orifice measured in pounds per square inch absolute.

[c] H_o is total pressure measured in pounds per square inch absolute.

[d] T_o is stagnation temperature measured in degrees Fahrenheit.

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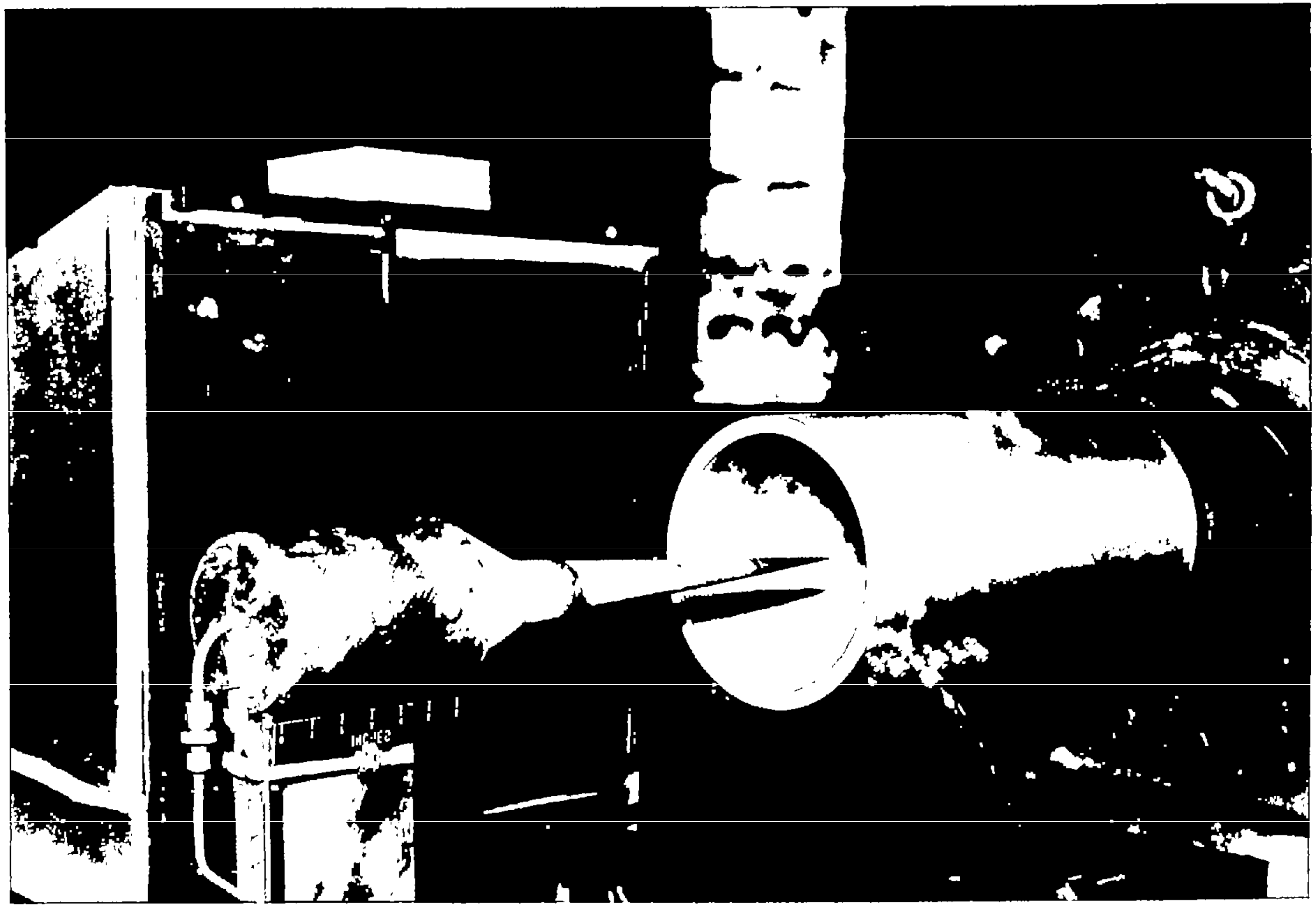

Figure 1.- Porous cone mounted in the free jet.

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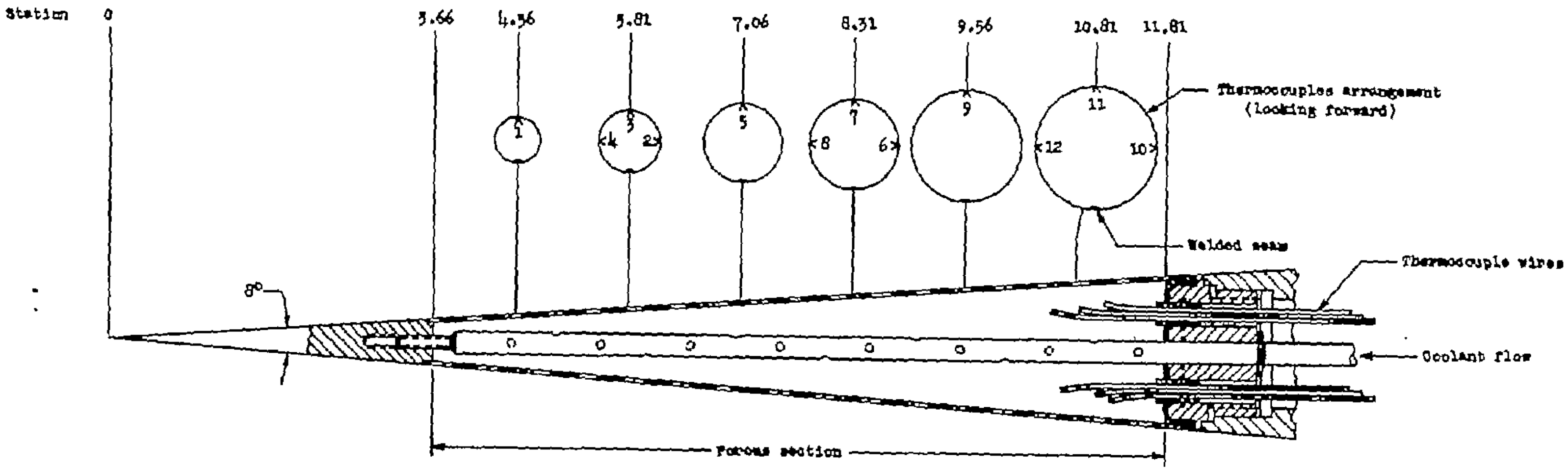

Figure 2.- Sectional view of cone showing arrangement of thermocouples and coolant flow apparatus. All stations are in inches.

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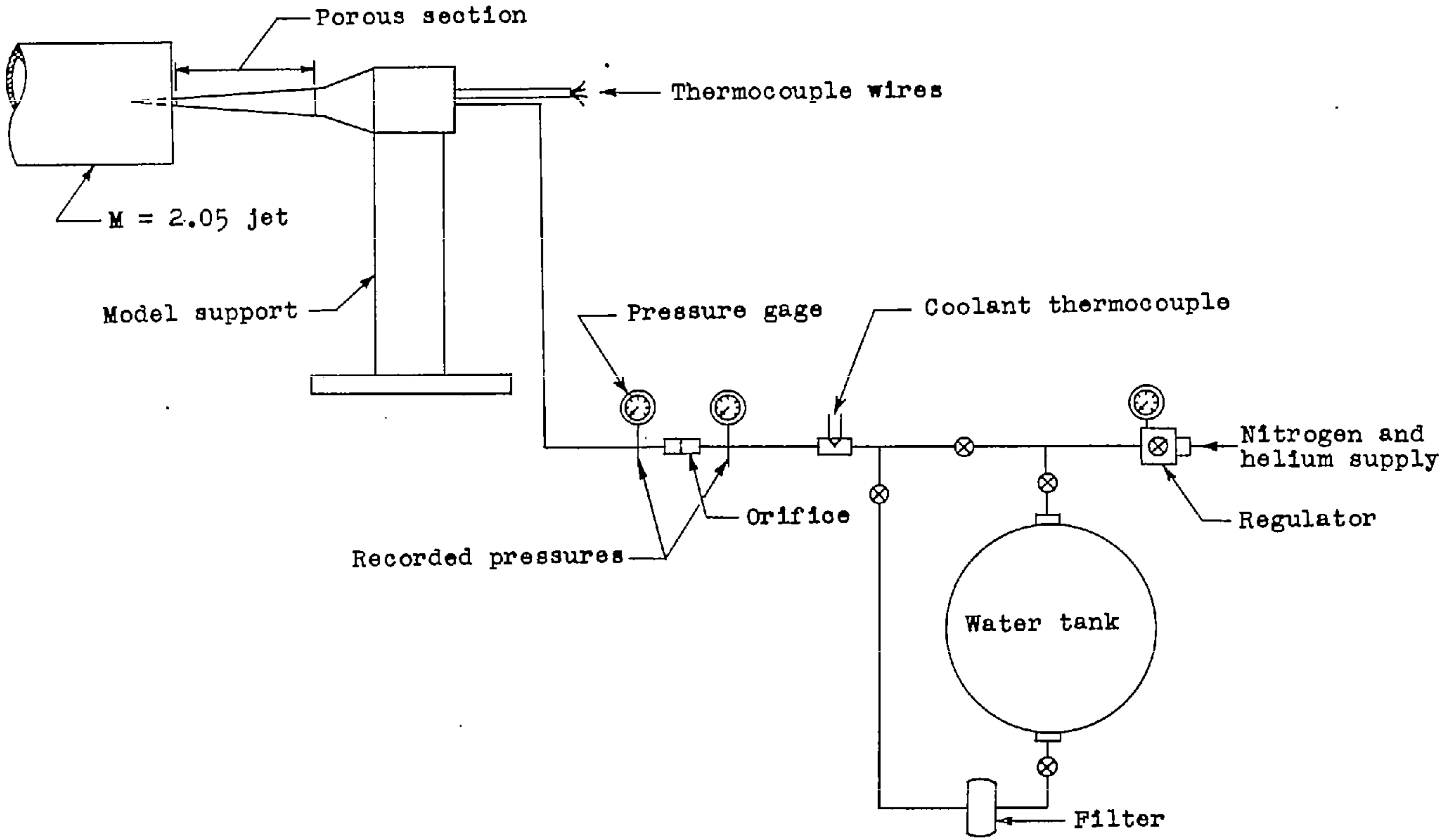

Figure 3.- Schematic drawing of coolant injection system.

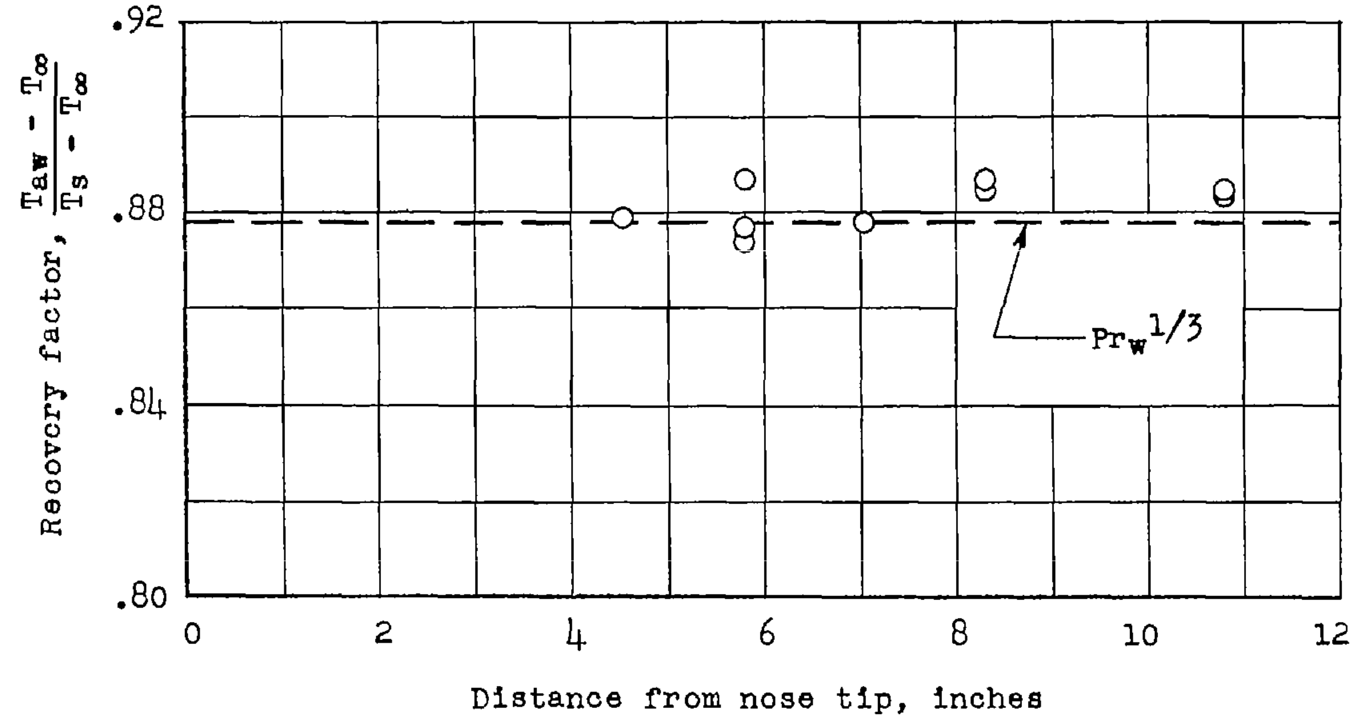

Figure 4.- Recovery factors for test with no coolant flow.

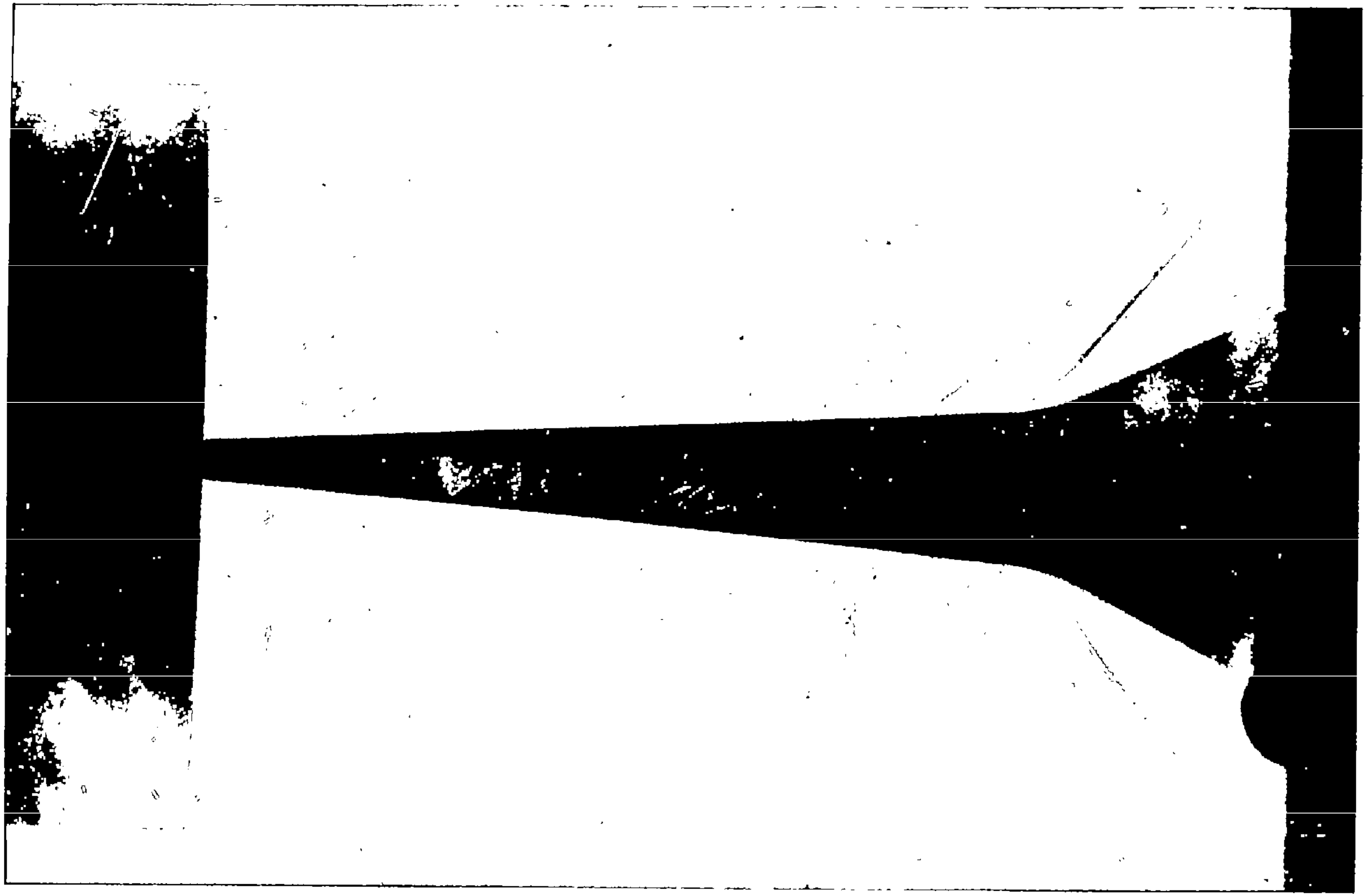

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Figure 5.- Shadowgraph made during a nitrogen-cooling test.

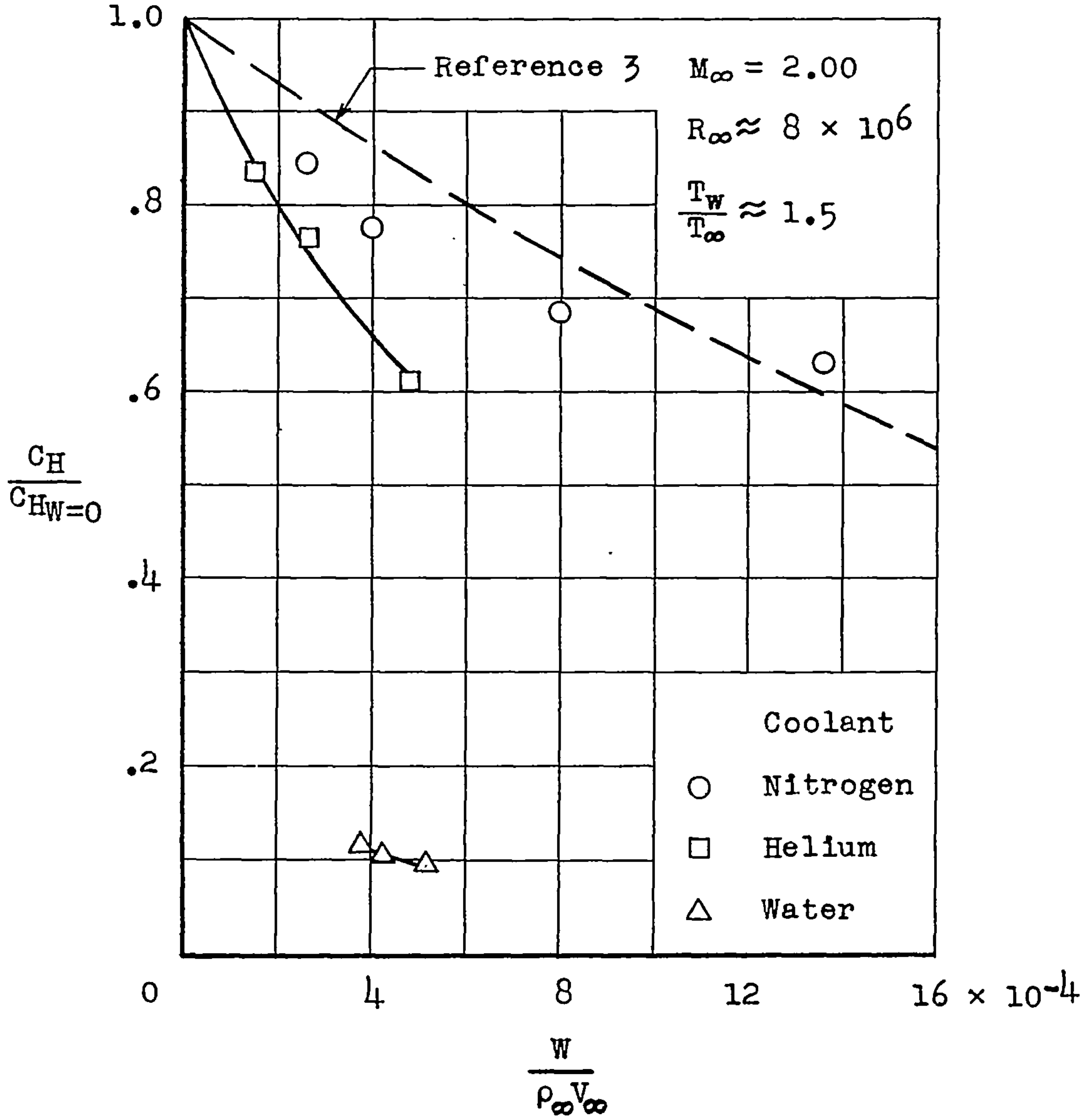

Figure 6.- Variation of average heat-transfer coefficient with mass-flow ratio.

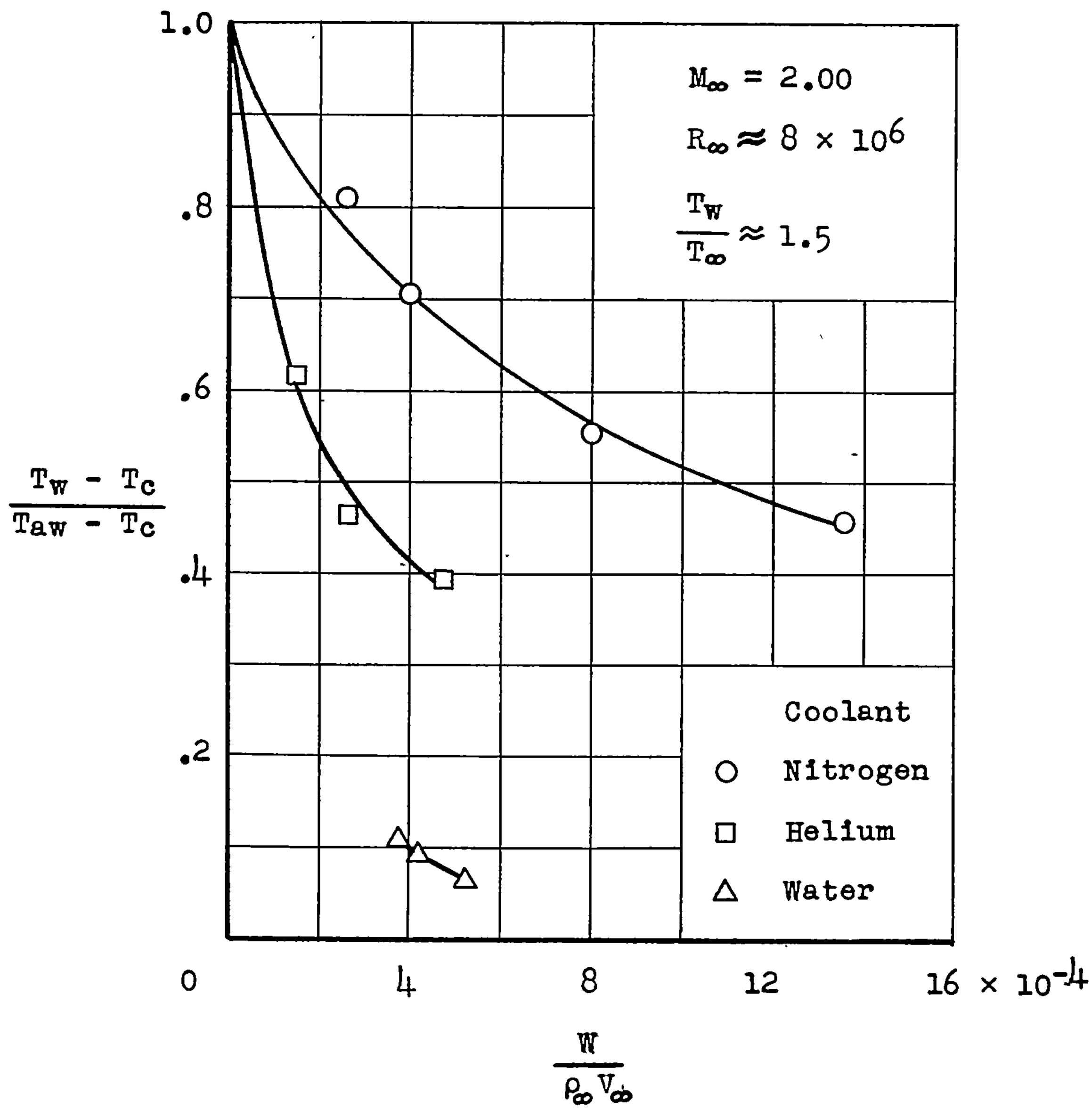

Figure 7.- Variation of average wall-temperature parameter with mass-flow ratio.

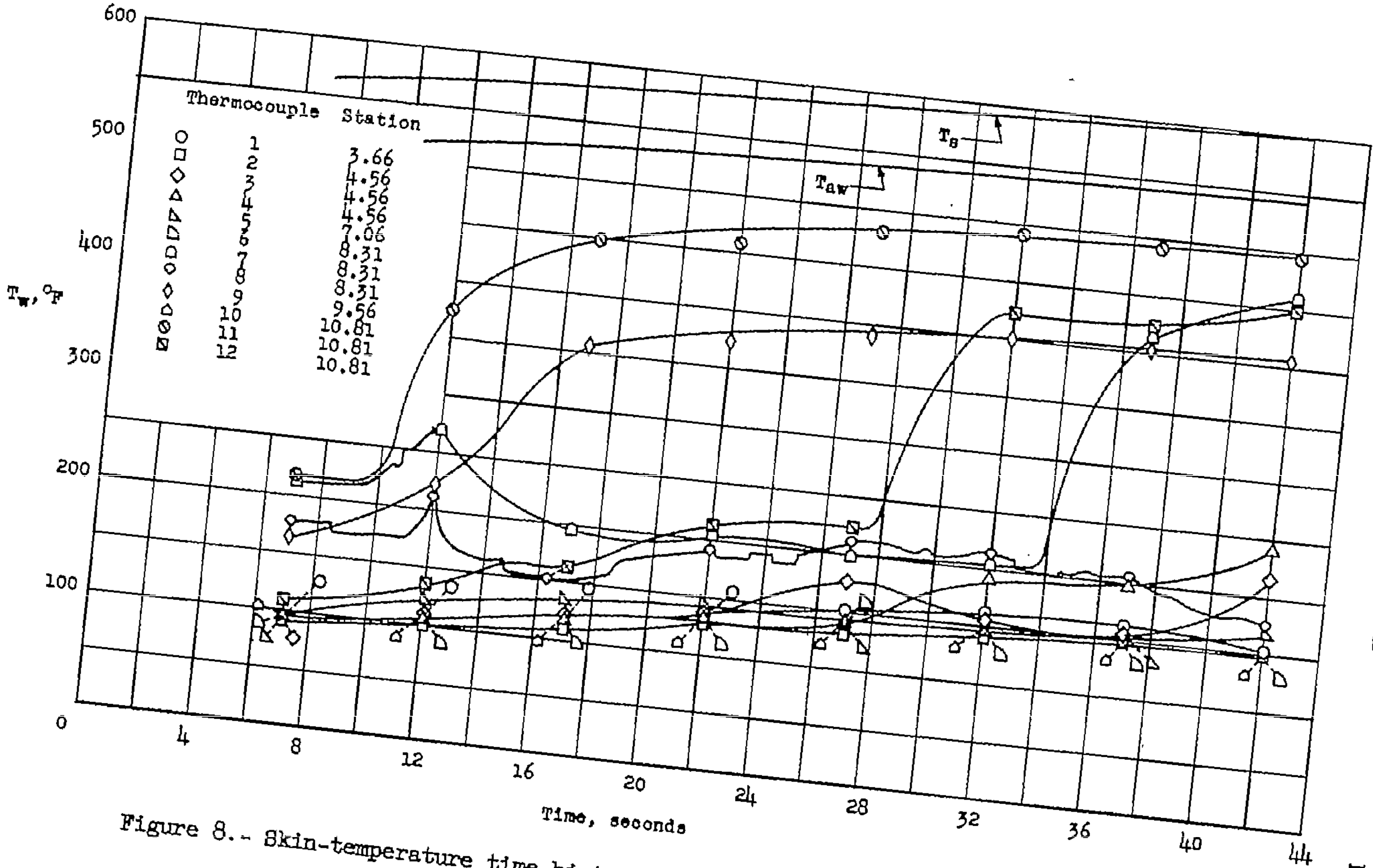

Figure 8.- Skin-temperature time history for the lowest rate of water cooling, 0.0074 lb/sec.